EDITOR'S CHOICE

The Impact of Dividing the Flexor Tendon Pulleys on Tendon Excursion and Work of Flexion in a Cadaveric Model

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CME Continuing Medical Education

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Learning Objectives

Upon completion of this CME activity, the reader will understand:

- The relative importance of the annular pulleys of the flexor tendon sheath.
- Expected alterations in tendon excursion after flexor pulley division.
- Expected alterations in tendon work after flexor pulley division.

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Purpose The A2 and A4 pulleys of the flexor tendon system have traditionally been considered critical components of efficient digital flexion. This dogma has recently been challenged. Using fresh human cadaveric hands and a model to measure force and excursion, we sought to clarify the clinical importance of releasing different pulleys.

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Methods Combinations of A1, A2, and A4 pulleys were released on the index, middle, ring, and little fingers of fresh, cadaveric hands. The excursion was measured as the distance the tendon was pulled by the motor to achieve palm touchdown. The force applied by the motor was constant (25 N); work was derived from the product of force and excursion (distance). The change in excursion and work needed to achieve palm touchdown before and after pulley release was measured. Excursion varies among digits and specimens at baseline; therefore, the percentage change from the intact state was used to compare groups. We compared A2 versus A1, A4 versus A1, A4 versus A2, A1 + A2 versus A2, and A1 + A4 versus A4.

Results Isolated A2 or A4 release had the greatest individual impact on the excursion (4.77% ± 1.52% and 3.88% ± 1.93%, respectively). When A1 was released with A2 (9.90% ± 2.52%), the additional impact on the excursion was significant; however, when A1 was released with A4 (2.63% ± 2.81%), the impact was marginal. No clinically or statistically significant change in the work of flexion was detected.

Conclusions A1 release was clinically significant when added to A2 release but not when added to A4 release. Sacrifice of the A2 and A4 pulleys resulted in a statistically significant, but clinically negligible, difference in flexor tendon excursion. These data suggest that the A1 pulley should be preserved when other proximal pulley components are likely to be compromised. These data also add further support to the concept that the A2 pulley or the A4 pulley can be released as needed for optimal tenorrhaphy.

Clinical relevance During flexor tendon repair, the length of contiguous pulley release may have more impact on final tendon excursion than which specific pulleys are released. *(J Hand Surg Am. 2021;46(12):1064–1070.*

Key words Flexor tendon excursion, flexor tendon pulleys, tendon repair.

Current and historical teaching holds that preservation of the A2 and A4 pulleys is critical to maintaining efficient digital flexion. This anatomy is most relevant during flexor tendon repair. However, this dogma has recently been challenged by raising important questions: Must the A2 and A4 pulleys truly remain intact? How much of the pulley system is truly needed to adequately preserve function? What quantitative measurement of finger flexion best correlates with function? How well do historical biomechanical studies correlate with real-life clinical scenarios?[1–3]

All these important questions remain essentially unanswered, and the *in vivo* biomechanics of the flexor pulleys remain unclear. Various biomechanical studies have focused on the importance of the flexor tendon pulleys and generally conclude that A2 and A4 are critical for efficient flexion. However, many of these studies may be outdated, and some used animal models.[4–7] Recent advancements in zone II flexor tendon repair and postoperative therapy protocols challenge the conclusions of these older biomechanical studies.

With a modern-day focus on early motion, the integrity of the repair is paramount.[2] Proper exposure of the tendon is critical to facilitate the best tenorrhaphy possible with no gapping and minimal bulk. Always preserving A2 and A4 pulleys during flexor tendon repair makes the procedure challenging when the injuries are located at, or around, these pulleys. Either venting (partial division of a pulley) or releasing (complete division of a pulley) can be used to improve exposure and can counteract a bulky repair and postoperative edema that inhibit tendon glide. Tang[3] argued that more liberal venting was well-tolerated and that bowstringing may not be functionally significant. Furthermore, resistance to glide may decrease after pulley venting, which might serve to offset the additional energy needed to flex a digit with a bowstringing tendon.

The objective of our study was to improve upon prior biomechanical studies by replicating certain approaches and concepts but using fresh cadaver human hands, designing more clinically relevant dissection, and measuring both excursion and work as surrogates for efficient digital flexion. To maintain a focus on clinically relevant scenarios and outcomes, we measured the excursion and work needed to recreate a meaningful grip as a finger traveled from repose (ie, open-hand static equilibrium) to palmar touchdown in the setting of vented pulleys. We hypothesized that no single portion of the pulley system was more important than another and that sacrificing any limited segment of the system would not result in clinically relevant changes in work or excursion for reaching palmar touchdown.

MATERIALS AND METHODS

Ten fresh, never-frozen, cadaver specimens were transected through the radiocarpal joint. Before use, all hands were evaluated fluoroscopically for evidence of preexisting skeletal trauma or arthritis. All fingers were dissected via midaxial incisions with oblique extensions into the palm, exposing the entire flexor pulley system. The hands were mounted on a custom frame with proximal flexor digitorum profundus (FDP) tendons separated and individually connected to a computer-controlled servomotor (Fig. 1). We confirmed that the FDP tendons were able to glide without obstruction or buckling of the flexor digitorum superficialis tendons, and the flexor digitorum superficialis tendons were otherwise not involved in the testing. The motor simulated full, active flexion of the digits individually. A load cell measured force throughout the arc of flexion and ensured force was limited to 25 N to achieve palm touchdown.

The control state was defined as a dissected digit with closed skin and no alterations to the pulley system. Flexor pulleys were sequentially released in a predetermined fashion, and the digits were tested in each state of release. The skin was sutured after each sequential pulley excision. The following combinations of pulley release were tested: A1 only, A2 only, A4 only, A1 + A2, and A1 + A4. After a digit was tested for 1 of the single pulley releases, it was then used to test combination releases. The A1 + A2 and A1 + A4 combinations were chosen to elucidate what affected flexion mechanics more: the total length of sheath opened, the total length of contiguous sheath opened, or the position of the opening along the sheath.

Data collection for a single run began when 1 N of opposing force was encountered (to account for slack) and concluded when 25 N of force was reached (palm resistance). A force of 25 N was used as the force-limit endpoint based on observations from pilot runs where 25 N reliably achieved palm touchdown in pretest fingers without pulley release. Between runs, the fingers were passively extended to the point of open-hand static equilibrium. Data recorded during each run included the distance the motor pulled until a palm resistance of 25 N was achieved (ie, excursion) and the pulling force of the motor throughout the run. Work of flexion (W_F) was calculated from the pulling force (F_P) and distance (D) measurements ($W_F = F_P \times D$).

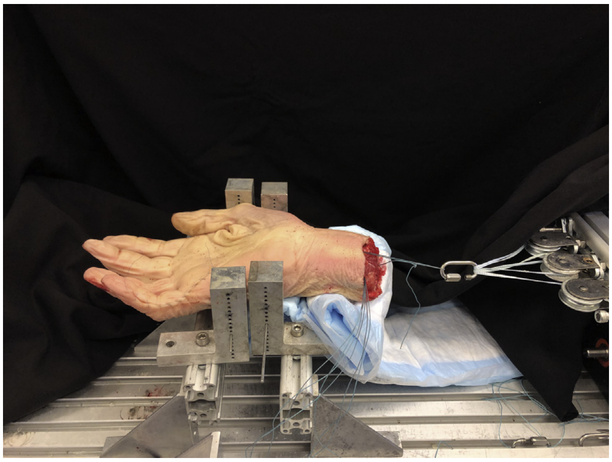

FIGURE 1: Experimental setup. Profundus tendon of the middle finger is being pulled.

TABLE 1. Change in Excursion

Pulley(s) Released	N	Percent Change Excursion (Mean ± SD)	Change in Excursion in mm (Mean ± SD)
A1	11	0.69 ± 1.22	1.46 ± 0.68
A2	15	4.77 ± 1.52	2.40 ± 0.85
A4	8	3.88 ± 1.93	2.05 ± 0.78
(A1 + A2)	11	9.90 ± 2.52	6.04 ± 1.77
(A1 + A4)	8	2.63 ± 2.81	2.25 ± 0.70

Data from 5 runs in each state of pulley release were averaged. To account for varying lengths of the digits and to pool data among all the specimens, each digit served as its own control. Percentage change of work and excursion was calculated for each finger in the experimental states of release and compared with the same calculations for the unaltered control states. A total of 10 hands and 37 digits were used. Seven digits were excluded for triggering or inability to achieve palmar touchdown with 25 N of force in the control state.

Two sample *t* tests assuming unequal variances were used to compare the means of the various states of the pulleys. Bonferroni-adjusted *P* values were compared with an α of 0.01. Although there are no set standards for clinically significant change in work of flexion or excursion, we took two approaches to evaluate our results. First, we used *post hoc* power

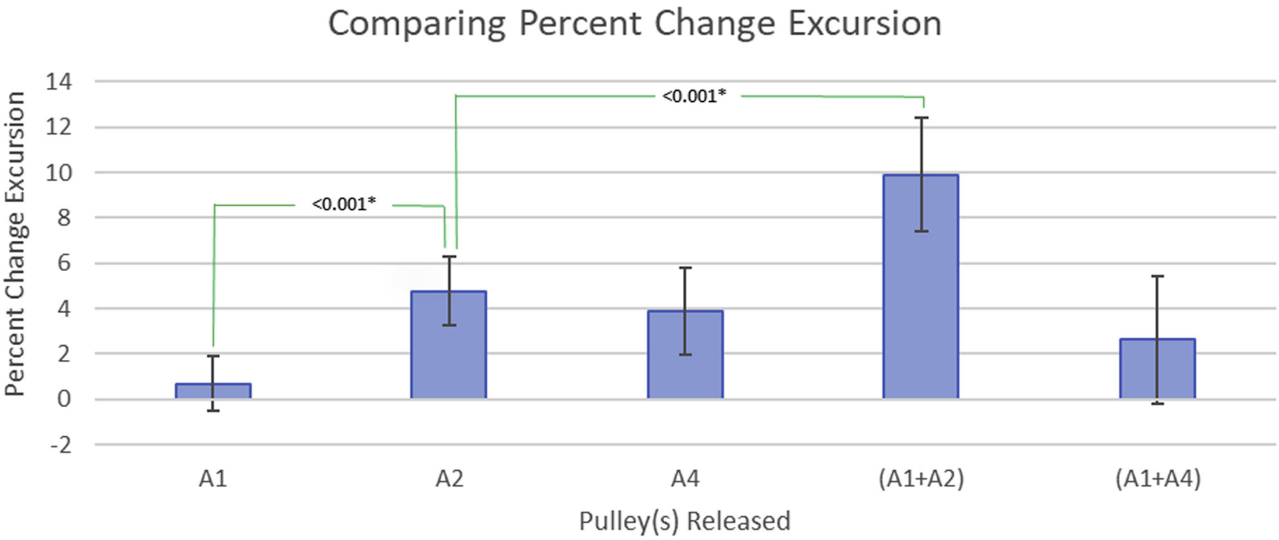

FIGURE 2: Comparing change in excursion between the different pulley release conditions. *Statistically significant.

TABLE 2. Comparing Change in Excursion

Groups	Percent Difference in Excursion* (Mean ± SE)	*P* value
A2 versus A1	4.07 ± 0.79	<.001†
A4 versus A1	3.19 ± 0.93	‡
A4 versus A2	−0.89 ± 0.88	‡
(A1 + A2) versus A2	5.13 ± 0.79	<.001†
(A1 + A4) versus A4	−1.24 ±1.00	‡

SE, standard error.

*Difference = ($\mu_{group1} - \mu_{group2}$).

†Significant at Bonferroni-corrected $\alpha = 0.01$.

‡Groups were underpowered; therefore, *P* values were not included.

TABLE 3. Change in Percent Work After Pulley Release

Groups	Change in Percent Work* (Mean ± SD)
A1	−0.976 ± 1.44
A2	0.707 ± 5.36
A4	0.306 ± 5.25
(A1 + A2)	3.26 ± 6.70
(A1 + A4)	−4.93 ± 9.11

*Difference = $\mu_{intact} - \mu_{release.}$

analyses using the 2-sided, 2-sample equal variance *t* test for the null hypothesis of equal means between groups. Second, we evaluated the percentage change as a relative indicator of the impact of each different pulley release combination to give broad clinical context.

RESULTS

On average, A1 was 22 mm long, A2 was 23 mm long, and A4 was 23 mm long; the overall average length of a single pulley was 22.5 mm (2.25 cm). Table 1 shows the change in excursion after isolated or combination pulley release. Positive percentage values indicated that after pulley release, the motor pulled the tendon unit a longer distance to achieve palm touchdown. Isolated A2 or A4 release had the greatest individual impact on the excursion. The greatest overall impact on the excursion occurred with a combined release of pulleys A1 and A2, resulting in an approximately 10% change in the excursion (Fig. 2).

Table 2 compares the percentage change of excursion between groups. The release of A2 had a statistically significant impact on the change in the excursion compared with the release of A1 alone. When A1 was released with A2, the additional impact was significant. The *post hoc* power analysis showed that groups A1 versus A2 and (A1 + A2) versus A2 achieved over 80% power to reject the null hypothesis of equal means at a significance level of 0.01 using a 2-sided 2-sample equal variance *t* test. The *post hoc* power analysis indicated that the other groups of comparisons were underpowered to reject the null hypothesis of equal means; however, their percentage difference in excursion was notably lower overall. Similarly, the change in the percentage of work after pulley release was overall low in each

TABLE 4. Comparing Work Between Groups

Groups	Percent Difference in Work* (Mean ± SE)
A1 versus A2	−0.804 ± 1.45
A1 versus A4	−0.404 ± 1.91
A2 versus A4	0.401 ± 2.31
A2 versus (A1 + A2)	−2.55 ± 2.45
A4 versus (A1 + A4)	5.24 ± 3.72

SE, standard error.
*Difference = $\mu_{intact} - \mu_{release}$.

group, and the difference in the change in work between groups was at most 5% (Tables 3, 4); however, these comparisons were also underpowered to reject the null hypothesis.

DISCUSSION

Prior anatomic and biomechanical studies support strict preservation of the A2 and A4 pulleys to avoid bowstringing and maintain full and efficient digit flexion after tendon injury and repair.[8,9] Following this dogma may lead the surgeon to place a premium on preserving these specific pulleys over optimal exposure of the injured tendon. Furthermore, approaching a finger with the mindset of preserving A2 and A4 may compromise surgical exposure and eliminate intraoperative findings-based decision making.

The historical data from which these recommendations arose were based on possibly outdated experiments that deserve reexamination. Focusing solely on excursion as a marker of function, Doyle and Blythe[4] concluded over 40 years ago that A2 and A4 pulleys were necessary for full excursion. Lin et al[5] had the same conclusion in 1989 and included joint angular motion as a more accurate surrogate for *in vivo* motion. Peterson et al[6] had similar conclusions; however, theirs was the first group to argue that flexion efficiency was best measured by W_F in addition to excursion because W_F takes the resistance of the surrounding tissue into account. Peterson's[6] study, which was undertaken in 1986, may not be directly applicable to real-world clinical scenarios because it used primate hands and excised the palmar skin, underlying lumbricals, and superficialis tendons. In 1996, Rispler et al[7] also concluded that A2 and A4 were critical pulleys. Though there were improvements in that study compared with others in that both excursion and W_F were measured and the dissections were clinically accurate, frozen cadaver hands were used, potentially changing the pliability and compliance of the soft tissues.[7]

We sought to reevaluate these prior findings supporting strict specific pulley preservation by replicating earlier studies but using an improved experimental model and fresh human hands. Fresh hands were an important aspect of our experimental model, as we strove to closely replicate clinical scenarios and eliminate factors that could have an unpredictable effect on the results. Such factors that may differ between thawed hands and never-frozen hands can include tissue compliance, tendon elasticity and stiffness, tendon lengths, tendon transverse diameters, and tendon tensile strength.[10–12] Similar to that of prior studies, our results show that sacrifice of either the A2 or A4 pulley, in isolation, has a statistically significant impact on the excursion needed to achieve palm touchdown. However, since the value of the change in excursion is minimal, this finding may not be clinically relevant. Most of our isolated or combination releases resulted in approximately 2 mm of lost excursion. This represented 3.5% of the average total excursion of the FDP, which had an excursion of approximately 57 mm across all digits studied. Clinical bowstringing was not visualized during data collection, which may be because skin was closed prior to applying a force to the tendons.

What is the smallest percentage loss of total FDP excursion allowable before a patient experiences an inability to achieve palm touchdown or meaningful fist formation? Could some of this lost excursion be mitigated through the inevitable small amount of tendon shortening that may occur with most tendon repairs? Though these questions were not directly addressed in this study, we do know from clinical experience that routine venting of the A4 pulley does not seem to affect the ability to achieve palm touchdown on attempted fist formation when a considerable amount of the fibroosseous sheath is left intact.[3] This suggests that selective permissive bowstringing and the resultant moderate loss of profundus excursion can be well-tolerated.

In this study, most pulley release groups resulted in minimal losses in profundus excursion, with the exception of the group in which the A1 and A2 pulleys were simultaneously released. The release of both A1 and A2 resulted in sizable discontinuity of the fibroosseous sheath and an approximately 10% loss of profundus excursion. These data from the A1 + A2 group suggested 2 findings. The first was that the role of A1 in flexion efficiency could be more important than previously thought, especially when other pulleys that were adjacent and distal to A1 were compromised or required venting to access and repair the injured tendon. The second was that contiguous pulley system loss, specifically the one that was greater than 2.25 cm (the average length of a single pulley in our study), seemed to be more important than any specific individual pulley loss. It was possible that the combination of A1 and A4 releases did not have an impact on the excursion because this pattern of pulley release did not result in a contiguous pulley system loss of more than approximately 2 cm. We hypothesized that having an intact contiguous length of fibroosseous sheath without loss of 2 cm or more likely kept the tendon in close approximation to the phalanges over a sizable distance and protected the moment arm mechanics throughout this length. Our findings provide biomechanical support to previous assertions by Tang et al[13] who similarly suggested allowable pulley loss of 2 cm, or perhaps up to 2.5 cm, based on clinical experience.

Peterson et al[6] argued that work, calculated as force multiplied by excursion, was a better measurement for the efficiency of the flexor tendon system. Theoretically, work takes into account the resistance of the surrounding soft tissues, which changes when the flexor sheath is opened. A changing moment arm may also be reflected in work. Our data did not show a percentage change in work greater than 5% from the baseline with any experimental group or a difference of greater than 5% between groups. This study was underpowered to reject the null hypothesis of equal means for work; however, these percentage comparisons suggested that there was minimal change in the work required to achieve palmar touchdown after pulley division. This is contrary to previous findings.[6] With fresh human hands, the change in tissue resistance after a released pulley may be minimal, whereas it may have been substantial in previously frozen hands. Our model used standard surgical approaches, with preservation of surrounding tissues and skin closure, which could also mitigate the work of motion when compared with findings from the literature.

The study was underpowered for excursion comparisons that included A4 and for work in general; however, the observed differences in excursion and work in these groups were relatively low. The study was powered to detect large differences in excursion and work as we believed that small differences in these measurements were unlikely to be clinically relevant. The results from this study suggest that the release of A2 in isolation, A4 in isolation, or A1 with A4 does not have a clinical impact, especially in comparison to the release of A1 with A2.

We argue that a change in tendon excursion that does not result in an appreciable change in fingertip palmar touchdown is not clinically significant. The change in excursion and work required to appreciate a change in palmar touchdown has not been defined. A similar conclusion was made by Soulii et al,[14] who showed that reconstructing the A2 and A4 pulleys resulted in measurable changes in tendon excursion and maximum joint rotational angles but that these changes may not be clinically relevant. Ultimately, what remains unanswered by this study and similar biomechanical studies are what amount of change in maximal rotational angle, work of finger flexion, and/or tendon excursion result in a functional deficit.

Notable limitations of our study are that the sample was underpowered for the excursion comparison groups containing A4, for work in general, and for reliance on clinical interpretation for these components. Another limitation is the clinical application of sacrificing a pulley without also performing an associated flexor tendon repair. Also, as with all cadaver studies, our model may not adequately represent true tendon surgery.

The findings of this study differ from that of historical biomechanical work but more closely resemble the real-world observations seen in modern clinical practice. These data suggest the A1 pulley should be preserved when other proximal pulley systems have been compromised or are likely to be vented. These data further support the concept that the A2 pulley or the A4 pulley can be vented as needed to facilitate an optimal tenorrhaphy. As a generalization from these data, 2 cm of venting may correspond to approximately 2 mm of excursion loss. Currently, the International Federation of Societies for Surgery of the Hand Flexor Tendon Committee and some experts argue that optimal exposure is critical to achieving a gap-free robust flexor tendon repair, which our findings support.[1,3,13,15] Rather than preserving anatomically named pulleys, our findings suggest that the surgeon can divide any section of the pulley system necessary to achieve an excellent tendon repair, with minimal clinical functional impact, as long as the division is limited to approximately 2.25 cm continuous length.

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JOURNAL CME QUESTIONS

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1. During surgery on the flexor tendons in the digits, traditional teaching would recommend preservation of which pulleys?

a. A1
b. A2
c. A1 and A3
d. A4
e. A2 and A4

2. What benefit may be provided by releasing flexor pulleys around zone 2 flexor tendon repair sites?

a. Prevention of bowstringing
b. Reduced resistance to tendon gliding
c. Fewer tendon adhesions
d. Reduced incidence of rupture
e. Less extensor lag

3. In this study, the greatest impact on tendon excursion occurred with what combination of pulley release?

a. A1 and A2
b. A2 and A3
c. A1 and A4
d. A3 and A4
e. All pulley release combinations produced similar change.

4. In this study, what was the final recommended continuous length of pulley system division without substantial presumed clinical impact?

a. 1 cm
b. 1.5 cm
c. 2 cm
d. 2.25 cm
e. 3 cm

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